

Field-crop-sprayer potential drift measured using test bench: Effects of boom height and nozzle type

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Abstract

Because of variations in environmental conditions, spray-drift field measurements following ISO 22866:2005 involve complicated and time-consuming experiments often with low repeatability. Therefore, simple, repeatable, and precise alternative drift assessment methods that are complementary to the official standards are required. One of the alternatives is the use of a drift test bench for field crop sprayers. Previous studies have demonstrated that the drift test bench can be considered an adequate complement to existing standard protocols for field drift measurements. In this study, in order to further improve the methodology and to evaluate the possibility of classifying different field-crop-sprayer settings according to drift risk using a test bench, a series of tests were performed in a test hall. A conventional mounted Delvano HD3 crop sprayer (Delvano, Kuurne, Belgium) equipped with an 800-l spray tank and a 15-m-wide stainless steel spray boom was used. Eight different sprayer setups were tested, involving three nozzle types (TeeJet XR 110 04, Agrotop TDXL 110 04 and Micron Micromax 3) and three boom heights (0.30, 0.50, and 0.70 m). For the drift classification, the reference sprayer drift behaviour was defined as that obtained using conventional flat fan TeeJet XR 110 04 nozzles operated at 0.30 MPa and at a boom height of

0.50 m. The different sprayer setups were successfully assigned to different drift reduction classes, and the results underlined the effects of nozzle type and boom height on the potential drift. The feasibility of the test-bench methodology for classifying field-crop-sprayer drift according to ISO 22369-1:2006 was demonstrated.

Keywords: sprayer setting, spray drift, droplet size, drift reduction, classification.

Nomenclature:

D	spray deposit measured on Petri dish ($\mu\text{l cm}^{-2}$)
A_s	absorbance (ABS, dimensionless) of Petri dish sample washing
A_0	absorbance (ABS, dimensionless) of blank Petri dish sample washing
A_t	absorbance (ABS, dimensionless) of tank solution
V	volume of deionised water (μl) used to elute sample
S	area of Petri dish collection surface (165 cm^2)
DPV	drift potential value (dimensionless)
D_i	spray deposit on single deposit collector placed in covered bench slots ($\mu\text{l cm}^{-2}$)
$D[v,0.1]$	Droplet size parameter. 10 th percentile
$D[v,0.5]$	Droplet size parameter. 50 th percentile
$D[v,0.9]$	Droplet size parameter. 90 th percentile
RSD	reference spray deposit under boom ($\mu\text{l cm}^{-2}$)
SE	standard error of the mean
VMD	Volume Median Diameter

1. Introduction

The requirements of the European Directive 128/2009/EC on the sustainable use of pesticides include the objective to reduce spray drift during application of agrochemicals to crops, especially

55 in the proximity of sensitive areas (e.g., water bodies, natural reserves, and urban areas). To achieve
56 this goal, various spray-drift mitigation measures can be adopted, which either affect the sprayer
57 components directly (e.g., the mounting of air-induction nozzles) or require sprayer adjustment.
58 Alternatively, indirect mitigation measures such as the construction of buffer zones and physical
59 barriers (e.g., hedges) along the borders of sprayed fields can be adopted. A combination of direct
60 and indirect spray-drift mitigation measures may facilitate minimisation of the widths of the buffer
61 zones established between the application areas and the sensitive zones, thereby increasing the land
62 surface available for cultivation.

63 In order to define buffer-zone widths, it is necessary to consider certain parameters, such as the
64 features of the sensitive area in question (e.g., the size of a water course), the toxicity of the applied
65 agrochemicals and, most importantly, the spray application parameters adopted for the
66 agrochemical distribution (Gilbert, 2000; Nilsson and Svensson, 2004). As regards the latter, it is
67 necessary to consider the sprayer type, nozzles, and operative parameters of the sprayer (Herbst and
68 Ganzelmeier, 2000; van de Zande et al., 2000; Nuyttens et al., 2007). In 2006, criteria to classify
69 spraying equipment according to drift risk were established (ISO 22369-1:2006). These criteria are
70 based on a relative comparison between the drift generated by the candidate spraying equipment
71 and a reference apparatus, which is selected as being representative of the most common spraying
72 technique adopted for a certain scenario (e.g., for application to field crops, vineyards or orchards).
73 To date, this relative comparison has been performed using drift measurement data that can be
74 obtained in the field, applying the ISO 22866:2005 test methodology (ISO 22866:2005), or in a
75 laboratory wind tunnel, following the ISO standard 22856:2008 (Nuyttens et al., 2011).

76 Both standardised test methodologies, however, have certain limitations. ISO 22866:2005
77 methodologies are designed for tests to measure the amount of drift outside the applied field for
78 defined wind-speed and -direction conditions. However, it is difficult to perform relative
79 comparisons between spraying results, as operation under the same wind conditions is required for a
80 successful comparison. Moreover, the test procedure itself is complex and time consuming and, as

81 regards spray application to arboreal crops, the results are affected by the morphological and
82 vegetative features of the orchard/vineyard in which the tests are performed. On the other hand, the
83 ISO 22856:2008 methodology facilitates the performance of relative comparisons more rapidly.
84 However, this comparison is primarily between nozzles rather than the full spraying system, as the
85 test procedure involves drift measurement in a wind tunnel with dimensions sufficient to contain
86 small boom sprayers only. Therefore, using ISO 22856:2008, it is difficult to compare the spray
87 drift generated by complete sprayers, since drift not only depends on the spray quality, but also on
88 the sprayer configuration and adjustment.

89 To overcome these limitations, researchers at the Dipartimento di Scienze Agrarie, Forestali e
90 Alimentari (DiSAFA) at the University of Torino (Turin, Italy), in collaboration with the Advanced
91 Agricultural Measurement Systems (AAMS)-Salvarani company (Maldegem, Belgium),
92 researched and developed an *ad hoc* test bench for the measurement of potential spray drift (Balsari
93 et al., 2007). Potential spray drift is defined as the percentage of initial spray volume that remains
94 suspended in the air after the sprayer passage and which represents the fraction of spray liquid more
95 susceptible to drift out of the treated area by the action of air currents during the application
96 process. It differs from the absolute spray drift because it consists only of a plume of droplets which
97 remain suspended in the air after the passage of the sprayer along the swath and these droplets
98 deposit sometime after the boom has moved over a given point. As potential drift has to be
99 measured in the absence of wind, its amount is not affected by wind velocity and direction, but it
100 depends only on the turbulence generated by the sprayer moving forward and is influenced by
101 boom height and size of the sprayed droplets. On the other hand absolute spray drift, according to
102 the definition given in ISO 22866 (2005) is represented by the “quantity of plant protection product
103 that is carried out of the sprayed (treated) area by the action of air currents
104 during the application process”. Its amount is therefore represented by all the spray that is applied
105 within the field but is blown out of target area by wind. Wind velocity and direction therefore
106 strongly affect absolute drift values, making it difficult to determine the influence of individual

107 sprayer parameters on the results obtained, particularly if the wind conditions vary. This is the
108 reason why, in order to make relative comparisons between spraying equipment in terms of drift
109 risk, measurement of potential drift was considered here to be a more suitable parameter for
110 providing objective and reproducible data since the influence of environmental conditions on the
111 results obtained is much less.

112 Researchers have promoted the establishment of an ISO standardised test methodology (ISO
113 22401:2015) for measuring the potential spray drift generated by field crop sprayers. During the
114 process of establishing the test method, the members of ISO TC23/SC6/WG 16 performed indoor
115 tests on field crop sprayers at the Praktijkcentrum voor Land- en Tuinbouw (PCLT) testing hall in
116 Roeselare (Belgium), which were primarily intended to assess the robustness of the proposed
117 methodology. During these tests, among other investigations, an evaluation of the potential spray
118 drift generated by different combinations of boom heights and nozzle types on a Delvano HD3
119 mounted field crop sprayer was conducted, using the test bench.

120 This paper reports on these tests and their findings, thereby clarifying the influence of boom height
121 and nozzle type on potential spray drift. Hence, the efficacy of the ISO 22401:2015 methodology
122 for classifying different field-crop-sprayer settings according to drift risk is evaluated, and discusses
123 the reproducibility of the test-bench-based results and its functionality.

124 **2. Materials and methods**

125 *2.1 Measuring set*

126 Tests were conducted at PCLT Roeselare in Belgium, in a test hall of approximately 60 m in length,
127 30 m in width, and 8 m in height, with a completely level earth floor (Fig. 1).

128 **[Insert Fig. 1]**

129 The environmental conditions (air temperature and relative humidity, wind speed and direction)
130 were measured and registered during the tests using an Allemano Testo 400 thermo-hygrometer
131 (Nuova Allemano, Collegno, Italy) and a Gill Windsonic sonic anemometer (Gill Instruments,

132 Hampshire, UK) at 1-Hz frequency. Instruments were positioned on one side of the test hall at 2 m
133 height from the ground.

134 All the tests were conducted at an average air temperature of 10°C (minimum and maximum: 8.7°C
135 and 11.3°C, respectively), an average relative humidity of 81% (minimum and maximum: 78% and
136 84%, respectively) and a very low average wind speed of 0.07 m s⁻¹ (minimum and maximum: 0.04
137 and 0.14 m s⁻¹, respectively). Thus, the environmental conditions for all of the performed tests were
138 stable and uniform. The tests were performed in accordance with the ISO 22401:2015 methodology
139 (ISO 22401:2015). The drift test bench consisted of an aluminium frame of 10.5-m length and 0.5-
140 m width, which contained slots for artificial collectors (plastic Petri dishes, 150-mm diameter;
141 Kartell, Milano). These artificial collector slots were positioned at intervals of 0.5 m and equipped
142 with sliding lids to ensure that the collectors could be completely covered. The test bench was
143 positioned such that the line of collectors was parallel to the driving direction and aligned with the
144 centre of the right-hand side of the spray boom (Fig. 1). Two slots at both extremities of the bench
145 were left permanently uncovered so that the effective overall spray deposition under the boom could
146 be measured. Deposit collectors were located at a height of approximately 0.25 m from the ground.
147 During each run, the boom sprayer moved at a set forward speed along a path of approximately 50
148 m in length, spraying over the covered test bench, which was positioned halfway along the spray
149 track. When the boom made contact with the actuator rod, the slots were automatically uncovered
150 by a pneumatic system. The actuator rod was always positioned 2.0 m behind the centre of the last
151 collector on the test bench, independent of the nozzle type used, in order to prevent the nozzles
152 from spraying directly onto the collectors.

153 To allow all the droplets suspended in the air to be deposited, but prevent accidental contamination,
154 the exposed Petri dishes were manually covered, but not until 60 s after the sprayer had passed.

155 After collecting the Petri dishes, all sliding covers were cleaned to prevent dripping liquid
156 contaminating the dishes.

158 2.2 *Spray application techniques*

159 The tests were executed using a conventional mounted Delvano HD3 field crop sprayer (Delvano,
160 Kuurne, Belgium) equipped with an 800-l spray tank and a 15-m wide stainless spray boom with
161 0.50 m nozzle spacing. The boom was mounted on a trapezoidal suspension, which ensured its
162 stability and horizontality. The sprayer was coupled to a New Holland 8260 tractor with 75-kW
163 power. All tests were performed at 6 km h⁻¹ forward speed.

164 Eight different spray application techniques were tested, with three repetitions for each setup (Table
165 1). Three different nozzle types (a TeeJet XR 11004 conventional flat-fan at 0.30-MPa pressure, an
166 Agrotop TDXL 11004 air-induction flat fan at 0.30 MPa, and Micron Micromax 3 rotary atomisers
167 operated at 0.28 MPa pressure and 2000 or 3200 rpm rotation speed) and three boom heights (0.30,
168 0.50, and 0.70 m) were considered. In accordance with previous studies (van de Zande et al., 2008),
169 the reference spraying technique was defined as operation of the TeeJet XR 11004 nozzles at 0.30
170 MPa with a 0.50-m boom height, at a constant forward speed of 6 km h⁻¹. This corresponded to an
171 application volume of 316 l ha⁻¹. The boom height was measured from the nozzle tip to the deposit
172 collectors. The effective forward speed was manually checked by measuring the time required by
173 the sprayer to cover a distance of 40 m along the spray track.

174 **[Insert Table 1]**

175 2.3 *Spray quality assessment*

176 The spray quality obtained for the various examined setups was evaluated through measurements of
177 the droplet size yielded by the three different nozzle types and the corresponding operative
178 parameters (Table 1). The droplet size measurements were performed at the DiSAFA Crop
179 Protection Technology laboratory of Turin University using a Malvern Spraytec laser diffraction
180 system (Malvern Instruments Ltd., Malvern, UK) equipped with a 750 mm lens and with dedicated
181 software. For each nozzle type, measurements were carried out on a single nozzle in fix position,
182 0.30 m above the laser beam, which targeted the spray jet in accordance with the nozzle axis. For
183 each of the four examined setups, the Malvern systems acquired data for at least 60 s for each

184 measurement, and the tests were repeated three times. The $D[v,0.1]$, $D[v,0.5]$, $D[v,0.9]$, and V_{100}
185 droplet parameters were calculated.

186 **[Insert Table 2]**

187 *2.4 Deposition measurements*

188 The spray solution consisted of a water solution with a tracer of Tartrazine E102 yellow dye (at a
189 targeted concentration of 10 g l^{-1}). This was prepared by pouring a weighed amount of the tracer
190 powder into the main spray tank, which contained a measured amount of clear water. Using the
191 sprayer agitation system, the solution was thoroughly mixed for at least 10 min to obtain a uniform
192 tracer concentration. Before each test, the boom was activated for approximately 60 s in order to
193 ensure all hoses and nozzles were primed with the spray solution. For each test, one 150-mm Petri
194 dish collector was placed in each test bench slot, resulting in a total of 22 collectors. As noted
195 above, two of these collectors were permanently uncovered.

196 Before each test run, two tank samples were taken from the nozzles in order to measure the actual
197 tracer concentration, while the sprayer was activated at the set operating pressure in a static
198 position. These samples were collected and then stored for laboratory analysis in order to obtain the
199 reference absorbance value.

200 The permanently uncovered collectors were manually washed in the laboratory using $100 \pm 1 \text{ ml}$ of
201 deionised water, and the other collectors (which were only exposed after the sprayer pass) were
202 washed with $10 \pm 1 \text{ ml}$ of deionised water. The washings were analysed using a WDR PC 1600
203 spectrophotometer set at an excitation wavelength of 434 nm (corresponding to the absorption peak
204 of the Tartrazine tracer). The spray depositions in the Petri dishes (D) were calculated according to
205 Eq. (1) and expressed in $\mu\text{l cm}^{-2}$, such that

206

207
$$D = \frac{(A_s - A_0)}{A_r} \times \frac{V}{S}, \quad (1)$$

208 where A_s is the absorbance (ABS, dimensionless) of the Petri dish sample washing, A_0 is the
 209 absorbance (ABS, dimensionless) of the washing from a blank Petri dish collected during the indoor
 210 tests, A_r is the absorbance (ABS, dimensionless) of the tank solution, V is the volume of deionised
 211 water (μl) used to wash the sample, and S is the area of the Petri dish collection surface (165 cm^2).
 212 The variation in the D_i obtained in the collectors positioned within the test bench and along the
 213 spray boom travel direction were plotted, in order to obtain the shape of the trailing plume
 214 generated during the spray process.

215

216 *2.5 Drift Potential Value Calculation*

217 The drift potential value (DPV) was calculated for each examined setup, following ISO
 218 22401:2015, on the basis of the sum of the spray deposits registered along the test bench. This
 219 calculation considered data from the collectors placed in the slots that were uncovered after the
 220 sprayer pass only (see Eq. (2)). The sum of these deposits was then divided by the reference spray
 221 deposit under the boom (RSD ; $\mu\text{l cm}^{-2}$), which was calculated for each individual test iteration
 222 based on the measured average nozzle flow rate and the effective forward speed. Thus,

$$223 \quad DPV = \sum D_i / RSD \times 100, \quad (2)$$

224 where D_i is the spray deposit on a single deposit collector positioned in the covered slots ($\mu\text{l cm}^{-2}$).
 225 The RSD value has a direct influence on the DPV calculation, but this parameter is calculated
 226 using the intended volume rate (1 ha^{-1}) for which the sprayer is calibrated. In order to verify the
 227 accuracy of the sprayer calibration and, therefore, the reliability of the RSD for the DPV calculation,
 228 two uncovered Petri dishes were placed at the extremities of the test bench for each spray run.
 229 These Petri dishes were used to determine the actual amount of spray deposit recovered under the
 230 boom.

231 .

232 *2.6 Statistical analysis*

233 The effects of the boom height and nozzle type on the *DPV* values were evaluated using one-way
234 analysis of variance (ANOVA) testing, followed by a *post hoc* comparison using a Tukey test ($P <$
235 0.05). The R statistical software package was used in all cases (R Development Core Team, 2012).
236 The data were transformed ($\ln [DPV/100]$) to yield residual normality and homoscedasticity prior to
237 the statistical analysis. Moreover, residual analyses were also conducted. In addition, the
238 relationship between the *RSD* and *Di* of the uncovered collectors ($\mu\text{l cm}^{-2}$), which were positioned
239 at distances 0 and 10.5 m along the test bench, were assessed.

240 **3. Results**

241 *3.1 Spray quality assessment*

242 The droplet-size measurements indicated that the TeeJet XR 11004 conventional flat-fan nozzle at
243 0.30 MPa produced medium droplets, according to the American Society of Agricultural Engineers
244 (ASAE) classification (Fig. 2a), with a non-negligible volume of fine droplets present in its
245 spectrum. Specifically, the $D[v,10]$ result was 70 μm (Table 2). Further, the Agrotop TDXL 11004
246 air-induction flat fan nozzle at 0.30 MPa produced very coarse droplets (Fig. 2b), with a $D[v,50]$ of
247 467 μm (Table 2), and a reduced amount of very fine droplets in the spray jet (the $D[v,10]$ result
248 was 186 μm). The Micron Micromax 3 rotary atomisers generated a more uniform spectrum of
249 droplets for both tested rotation speeds, as their sizes ranged between 150 and 500 μm . Further,
250 there was a complete cut-off of fine droplets of fewer than 100 μm in size (Table 2). In addition, the
251 $D[v,10]$, $D[v,50]$, and $D[v,90]$ values were more similar to one another than in the case of the flat
252 fan hydraulic nozzles. Therefore, the cumulative volume trend in relation to the droplet size for the
253 rotary atomiser was very different to the trends observed for the hydraulic nozzles (Fig. 2c and 2d).

254 **[Insert Fig. 2 and Table 2]**

255 *3.2. Indoor trials*

256 *3.2.1 Effect of boom height*

257 For both of the examined flat-fan nozzle types, it was found that the boom height has a significant
258 effect on the *DPV* values (Table 3). For a boom height of 70 cm, the drift was significantly higher
259 than that for 50 cm, followed again by that for 30 cm (Fig. 4). For conventional hydraulic nozzles, it
260 is worth noting that the *DPV* value registered at 70-cm boom height was double (55 ± 3) the *DPV*
261 obtained for the 50-cm boom height (25 ± 0.4). Furthermore, the latter value was twice the *DPV*
262 measured at the 30-cm boom height (12 ± 1). A similar trend was observed for the air-induction
263 nozzles.

264 In absolute terms, the *DPV* values obtained using the conventional flat-fan nozzles at 30-cm boom
265 height ($DPV = 12 \pm 1$) were very close to those obtained using the air-induction flat fan nozzles at
266 70-cm boom height ($DPV = 11 \pm 1$). Considering the obtained *DPV* value trend, it is also clear that
267 the effect of boom height is independent of nozzle type (Table 3). These results are in accordance
268 with the recommendations concerning optimal boom height made by various researchers in the
269 ambit of the Train Operators to Promote Best Management Practices and Sustainability (TOPPS)
270 project (see the “Best Management Practices to reduce spray drift” document on the TOPPS website
271 (TOPPS, 2015)).

272 The boom height also affected the variability of the results obtained for the various test iterations.
273 Higher standard errors of the mean (SE) values (Fig. 3) were obtained when the boom height was
274 increased; this was particularly evident in the case of the conventional flat-fan nozzles.

275 **[Insert Fig. 3, Table 3]**

276 *3.2.2 Effect of nozzle type*

277 Significant differences among nozzle types were also found (Table 3). For 50-cm boom height, the
278 largest (25.2) and smallest (1.9) *DPV* values were obtained for the conventional nozzles and the
279 Micron Micromax 3 rotary atomisers at 2000 min^{-1} rotation speed, respectively (Fig. 4). Significant
280 differences in terms of *DPV* were also found between the two rotation speed settings of the
281 atomisers (Fig. 4).

282 A detailed analysis of the combined effects of nozzle type and boom height indicates that
283 conventional flat-fan nozzles are much more strongly affected by boom height than air-injection
284 nozzles. This behaviour can be also linked to the droplet sizes and spectral distributions (D50 values
285 of 193 and 497 μm for conventional and air-injection flat fan nozzles, respectively, and D10 values
286 of 70 and 186 μm values for the same nozzles, respectively). Note that these results also
287 demonstrate the efficacy of the test bench for drift evaluation purposes and for discrimination
288 between the factors affecting drift. Further, these findings are in line with those obtained by Balsari
289 et al. (2007).

290 As regards the comparison of the effect of nozzle type at the standard recommended boom height
291 for flat fan nozzles (50 cm), it is interesting to note (Fig. 4) the large and statistically significant
292 difference between conventional and air-injection flat-fan nozzles, with the air-injection nozzles
293 generating a drift potential less than three times that of the conventional nozzles. In these tests,
294 rotary atomisers were also included, and two different droplet size spectra were obtained by
295 modifying the rotation speed (2000 and 3200 rpm). Despite the different nozzle designs, the results
296 indicate that the rotary atomisers have similar tendencies to flat-fan nozzles, with a significantly
297 lower drift potential that corresponds to a coarser spray quality.

298 **[Insert Fig. 4 and Table 5]**

299 *3.2.3 Deposition curves*

300 Figure 5 shows the curves obtained for the conventional and air-injection nozzles at the three
301 examined boom heights. A detailed analysis of these curves indicates that the majority of the spray
302 deposits were located within the first 4 and 2 m of the test bench when conventional and air-
303 induction nozzles were employed, respectively. However, the trailing plume shape was very similar
304 for each nozzle type, and the different boom heights affected the magnitude of the spray deposits
305 only; therefore, the *DPV* values were affected, but the spray deposition along the test bench was
306 not.

To consider the complete curve for the DPV calculation requires taking into account the whole of the plume of droplets that remains suspended in the air after the boom sprayer passed, especially the finer droplets which are more susceptible to drift. The spray deposit collected on the first dish of the test bench, uncovered just after the sprayer pass, often represents the highest drift deposit on the test bench, but this is not always true. The trend of the deposits on the test bench, does generally decrease but not always in a systematically, showing some “waves” (see Fig. 5). These irregular trends of spray deposits along the test bench are more evident when finer spray (i.e. produced by conventional nozzles) and boom heights over 50 cm are used. The analysis of the whole plume of droplets therefore provides more complete information about the potential drift risk.

Figure 6 shows the deposition curves obtained for the two examined rotary atomisers. As expected, higher D_i spray deposition values were found towards the upper end of the test bench when the Micromax 3 nozzles were operated at a rotation speed of 3200 rpm, which generated finer droplets. However, when the rotation speed was reduced to 2000 rpm, yielding a coarser spray quality, very low spray deposits were observed on the test bench collectors.

If nozzle type is the only variable considered in the deposition curve evaluation (Fig. 6), then the influence of droplet size and droplet spectrum uniformity are clear. The conventional flat-fan nozzles generated droplets with a $D[v,0.1]$ of 70 μm and a V_{100} of 24.2% (see Table 2), whereas the rotary atomisers yielded a $D[v,0.1]$ value of 206 μm with 0% for V_{100} . These factors, combined with the significant differences in terms of the volume application rates between the hydraulic and centrifugal nozzles, seem to have an important effect on the drift potential.

[Insert Fig. 5 and 6]

3.2.4 Relationship between RSD and uncovered Petri dishes

In all tests the recovery rate on the permanently exposed collectors was always >70% of RSD, as recommended by ISO 22401, proving that the test procedure was followed appropriately. Figure 7 shows the relationship between the theoretical RSD values (based on the intended spray volume expressed in $\mu\text{l cm}^{-2}$) and the actual spray deposits recovered under the boom in all of the tests. In

333 general, the relationship between the *RSD* and the spray deposit detected on the uncovered
334 collectors resulted similar for both test-bench extremities and results were more strictly correlated
335 when the centrifugal nozzles were employed, with respect to the conventional and air-induction flat-
336 fan nozzles. In all the tests examined the variability of deposits on the permanently uncovered
337 collectors, assessed by the three replicates, resulted in similar values at the beginning (0 m) and at
338 the end of the test bench (10.5 m), with CV values generally around 10%. In the eight tests
339 examined the average ratio between the deposit under the boom and the corresponding RSD ranged
340 between 86% and 104%. Considering all the tests examined, however, any relationship ($P < 0.05$)
341 was found between the ratio of the deposit under the boom vs. the corresponding RSD and the DPV
342 obtained.

343 **[Insert Fig. 7]**

344 *3.2.5 Relationship between DPV and spray quality*

345 The *DPV* values were also compared in relation to the droplet size spectrum generated by each
346 evaluated nozzle. Figure 8 shows the relationship between the *DPV* values and the four most widely
347 used droplet-spectrum indicators: $D[v,0.1]$, $D[v,0.5]$, $D[v,0.9]$, and V_{100} (ASABE, 2009; ISO,
348 2011). Some trends between these parameters and the *DPV* results were found, especially in the
349 case of $D[v,0.1]$. These results are clearly in accordance with those obtained in previous studies,
350 where the correlation between V_{100} and the total spray drift was very strongly demonstrated (Legg,
351 1983; Bode, 1984; Miller, 1988; Western et al., 1989; Bouse et al., 1990; Combellack et al., 1996;
352 Baetens et al., 2008; Arvidsson et al., 2011; Gil et al., 2014). **[Insert Fig. 8]**

353 *3.2.6. Drift reduction*

354 By comparing the average *DPV* values obtained for the eight examined sprayer settings, it was
355 observed that, in the majority of the cases, the potential drift was lower than that of the reference
356 value (TeeJet XR 11004 conventional flat-fan nozzles operated at 50-cm boom height). Only when
357 the boom height was increased to 70 cm for the conventional nozzles was a *DPV* value higher than
358 the reference obtained (Table 4). A very high reduction ($> 90\%$) in the potential drift with respect to

359 the reference sprayer setting was obtained when the air-induction nozzles were operated at 30-cm
360 boom height, and also when the rotary atomisers were operated at 2000-rpm rotation speed and at
361 50-cm boom height.

362 **[Insert Table 6 and Table 7]**

363

364 **4. Discussion**

365 The experimental results confirmed the conclusions of previous studies (Gil et al., 2014; Gil et al.,
366 2015), i.e., that the test methodology used to assess the potential drift of field crop sprayers
367 described in ISO Standard 22401:2015 is appropriate, and that it facilitates successful
368 discrimination between the *DPV* values obtained for a single sprayer with different test settings
369 (e.g., different nozzle-type and boom-height combinations). Applying the drift reduction classes
370 established in ISO 22369-1:2006 to the experimental *DPV* results, it was, in fact, possible to assign
371 six sprayer setups to particular drift reduction classes (Table 5). The reference *DPV* value obtained
372 using conventional flat-fan nozzles at a boom height of 50 cm was retained throughout the tests.
373 This classification yielded reliable results, indicating that the coarser the sprayed droplets and the
374 lower the boom height, the smaller the drift. (This confirms the results obtained by Balsari et al.
375 (2007)). Further tests are currently being conducted in order to verify whether the classifications
376 obtained for the examined sprayer settings using the test bench to evaluate the potential drift are
377 consistent with those obtained for the same sprayer settings under application of the ISO
378 22866:2005 test methodology (spray drift measurement in the field) or the ISO 22856:2008 test
379 methodology (spray drift measurement in a wind tunnel).

380 The obtained results also demonstrate that the indoor use of the test bench facilitates reduced the
381 variance of the results since the coefficient of variation between the three *DPV* values obtained for
382 each examined setup was always found to be within 15%.

383

384 **5. Conclusions**

385 This study presented an evaluation of the potential spray drift generated by different combinations
386 of boom heights and nozzle types for a Delvano HD3 mounted field crop sprayer, using a
387 previously designed test bench. The experimental results confirmed the robustness of the ISO
388 22401:2015 test methodology for the measurement of the potential spray drift generated by field
389 crop sprayers, with the aim of classifying different sprayer settings according to drift risk.
390 Concerning boom height and nozzle type boom sprayer setting parameters, test results showed the
391 capability of the test bench and relative ISO standard methodology (ISO 22401) to recognise their
392 significant effect on DPV. The use of air-induction nozzles compared to standard nozzles at the
393 same working height, enabled to reduce potential drift between 56% and 91% (see Table 4).
394 Lowering of boom height from 70 to 50 cm allowed to reduce DPV by 55% and 36% using the
395 standard and the air induction nozzles respectively (see Table 4). Further, as the use of test bench
396 facilitates indoor operation, it allows effective results to be obtained within a short period of time,
397 because the reproducibility of the results is very high. Moreover, the ISO 22401:2015 test
398 methodology facilitates comparison of sprayer settings according to drift risk using the full field-
399 crop-sprayer apparatus, similar to field-operation conditions, and not just with a sprayer component
400 (e.g., a nozzle). Because of the simplicity of this method and the reproducibility of the results, it is
401 expected that very similar results could be obtained in different laboratories around the world for
402 the same sprayer settings. The use of an indoor test bench can therefore be considered to be an
403 effective approach to performing a rapid and reliable drift classification of field crop sprayer
404 settings. On one hand, the indoor test bench allows the complete sprayer to be employed, as in field
405 treatments, and on the other hand, the results are not affected by the variable and unpredictable
406 outdoor environmental conditions. Further refinements of the *DPV* calculation method are
407 envisaged in order to facilitate comparison between the potential drifts obtained for sprayer trial
408 setups involving different forward speeds (Nuyttens, 2016).

409

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415

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481

482 **Figure Captions**

483 Fig. 1: PCLT test hall in Roeselare (Belgium), where the experimental trials were conducted.

484

485 Fig. 2: Cumulate volume curves as functions of droplet size measured by Malvern Spraytec system
486 for spray jet generated by: (a) TeeJet XR 11004, (b) Agrotop TDXL 11004, (c) Micron Micromax 3
487 (2000 rpm), and (d) Micron Micromax (3200 rpm) nozzles, and comparison with ASAE
488 classification. VF = very fine; F = fine; M = medium; C = coarse; VC = very coarse; XC =
489 extremely coarse; UC = unclassified.

490

491 Fig. 3: *DPV* values according to nozzle type and boom height. The different letters for each nozzle
492 type indicate significant differences in response to boom height variations (post hoc Tukey test, $P <$
493 0.05). The bars indicate the mean + SE.

494

495 Fig. 4: *DPV* values according to nozzle type for 50-cm boom height. The different letters indicate
496 significant differences among the nozzle type results (post hoc Tukey test, $P < 0.05$). The bars
497 indicate the mean + SE.

498

499 Fig. 5: Spray-deposit profiles for two different nozzle types (TeeJet XR 11004 and Agrotop TDXL
500 11004) and three boom heights (30, 50, and 70 cm). The mean \pm SE ($\mu\text{l cm}^{-2}$) of the spray deposit
501 on the collectors at each interval along the test bench is shown.

502

503 Fig. 6: Spray-deposit profiles for different nozzle types (TeeJet XR 11004, Agrotop TDXL 11004,
504 Micron coarse drops, Micron fine drops) at 50-cm boom height. The mean \pm SE ($\mu\text{l cm}^{-2}$) of the
505 spray deposit on the collectors at each interval along the test bench is shown.

506

507 Fig. 7: Relationship between RSD ($\mu\text{L cm}^{-2}$) and Di on uncovered collectors ($\mu\text{l cm}^{-2}$) located at 0
508 (left) and 10.5 m (right) along the test bench.

509

510 Fig. 8: DPV values according to droplet size expressed in terms of $D[v,0.1]$ (upper left), $D[v,0.5]$
511 (upper right), $D[v,0.9]$ (bottom left), and V_{100} (bottom right).

512

513

514 **Tables**

515 Table 1: Setups examined in experiments.

Setup	Nozzle type	Operating pressure (MPa)	Boom height (cm)	Volume application rate (l ha ⁻¹)
1	TeeJet XR 11004	0.30	30	316
2	TeeJet XR 11004	0.30	50	316
3	TeeJet XR 11004	0.30	50	316
4	Agrotop TDXL 11004	0.30	30	316
5	Agrotop TDXL 11004	0.30	50	316
6	Agrotop TDXL 11004	0.30	70	316
7	Micron Micromax 3 (2000 rpm)	0.28	50	110
8	Micron Micromax 3 (3200 rpm)	0.28	50	110

516

517

518 Table 2: Droplet size parameters measured for tested nozzles using Malvern Spraytec instrument.

Nozzle type	Pressure (MPa)	D[v,0.1] (µm)	D[v,0.5] (µm)	D[v,0.9] (µm)	V ₁₀₀ (%)
TeeJet XR 11004	0.30	70	193	429	24.2
Agrotop TDXL 11004	0.30	186	467	764	4.4
Micron Micromax 3, 2000 rpm	0.28	286	344	415	0.0
Micron Micromax 3, 3200 rpm	0.28	206	241	282	0.0

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523 Table 3. Results of two-way analysis of variance considering nozzle type (XR and TDXL and
524 height (30, 50 and 70 cm) as a source of variation

Source of variation	Df	Sum Sq	Mean Sq	F value	Pr(>F)
nozzle type (N)	1	10.578	10.578	194.885	1.31e-09
height (H)	2	7.531	7.531	138.746	1.19e-08
N x H	2	0.011	0.011	0.195	0.666
Residuals	14	0.760	0.054		

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Table 4: Summary of average *DPV* values obtained for eight different examined sprayer setups and differences with respect to reference *DPV* value. The reference *DPV* value is that achieved using conventional flat-fan nozzles at 50-cm boom height.

Nozzle type	Boom height (cm)	Average DPV	Relative difference vs. reference DPV
TeeJet XR 11004	30	12	-52%
	50	25	0
	70	55	+ 119%
Agrotop TDXL 11004	30	2	- 91%
	50	7	- 72%
	70	11	- 56%
Micron Micromax 3, 2000 rpm	50	2	- 92%
Micron Micromax 3, 3200 rpm	50	11	- 55%

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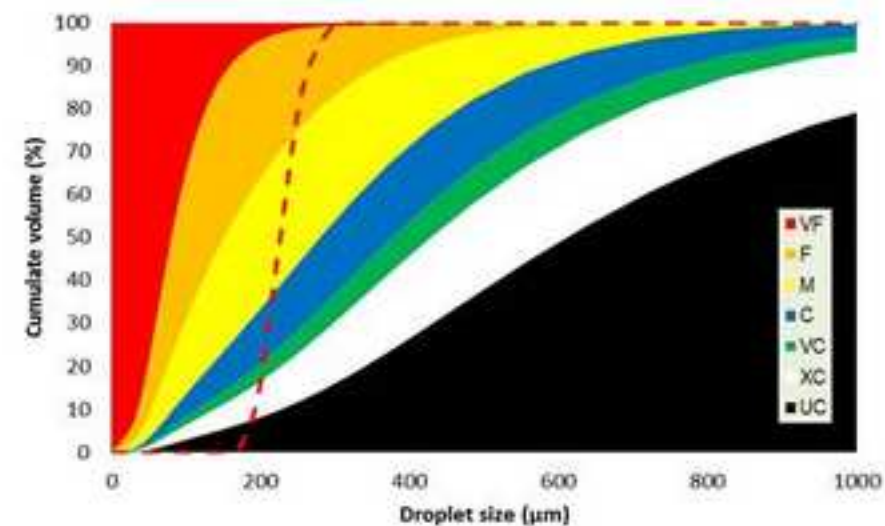
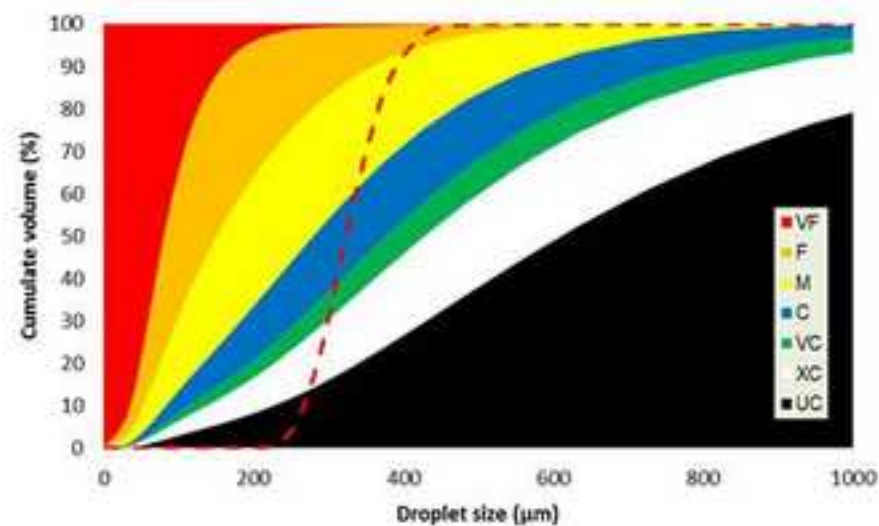
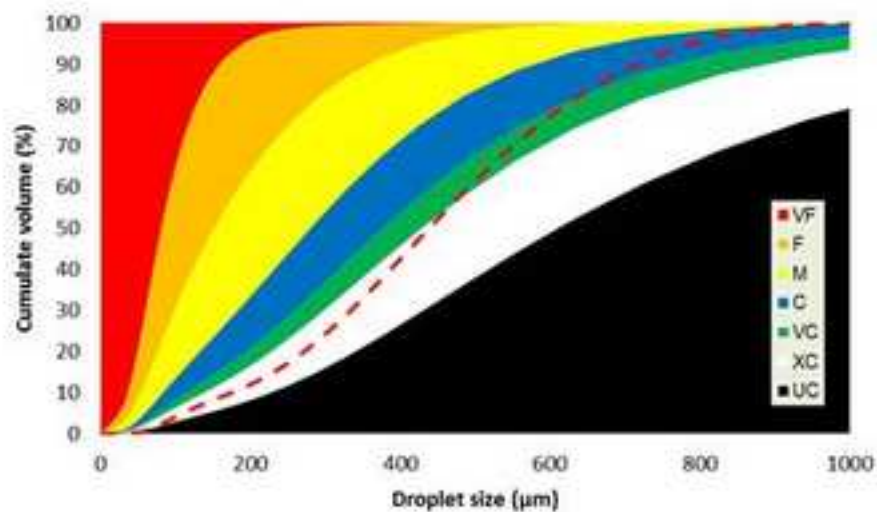
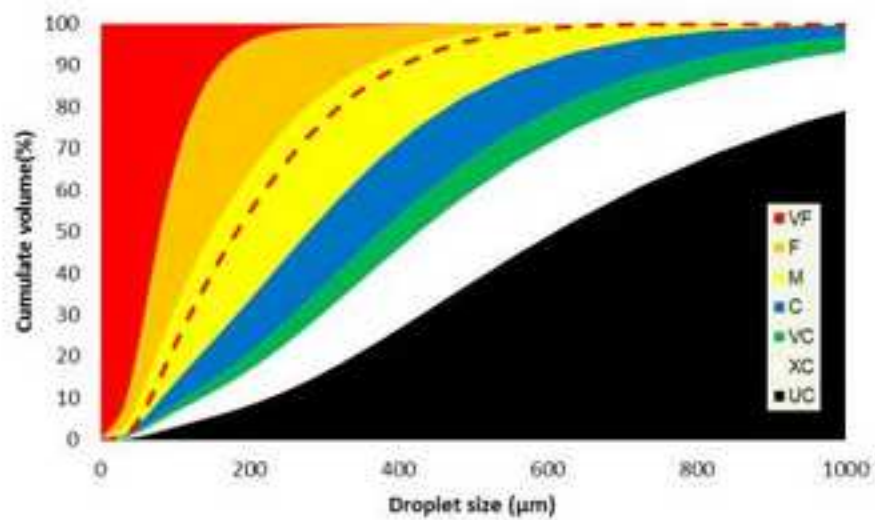
537 Table 5: Summary of average *DPV* values obtained for 8 different examined sprayer setups and
538 corresponding drift reduction classes vs. reference setting, assigned in accordance with ISO 22369-
539 1:2006.

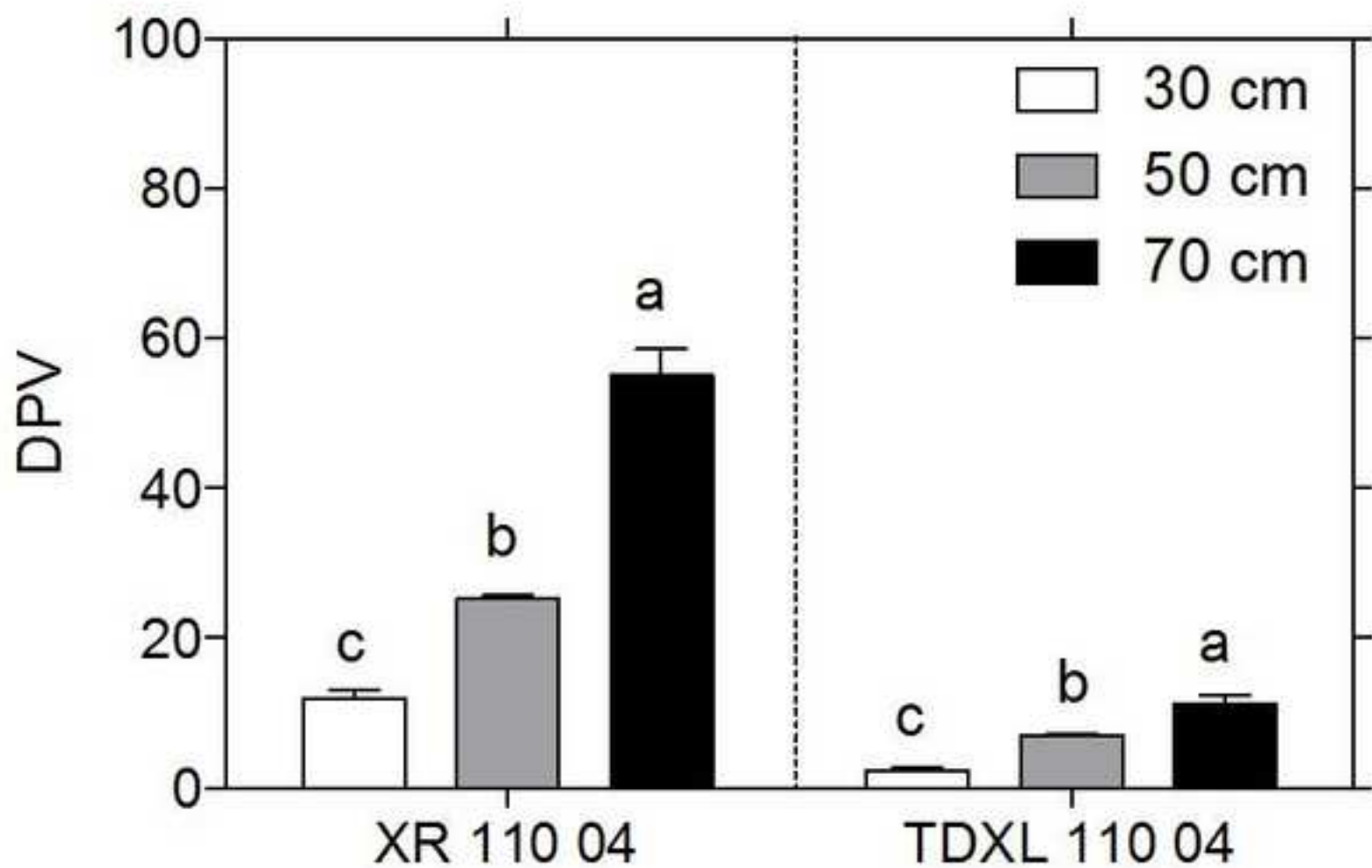
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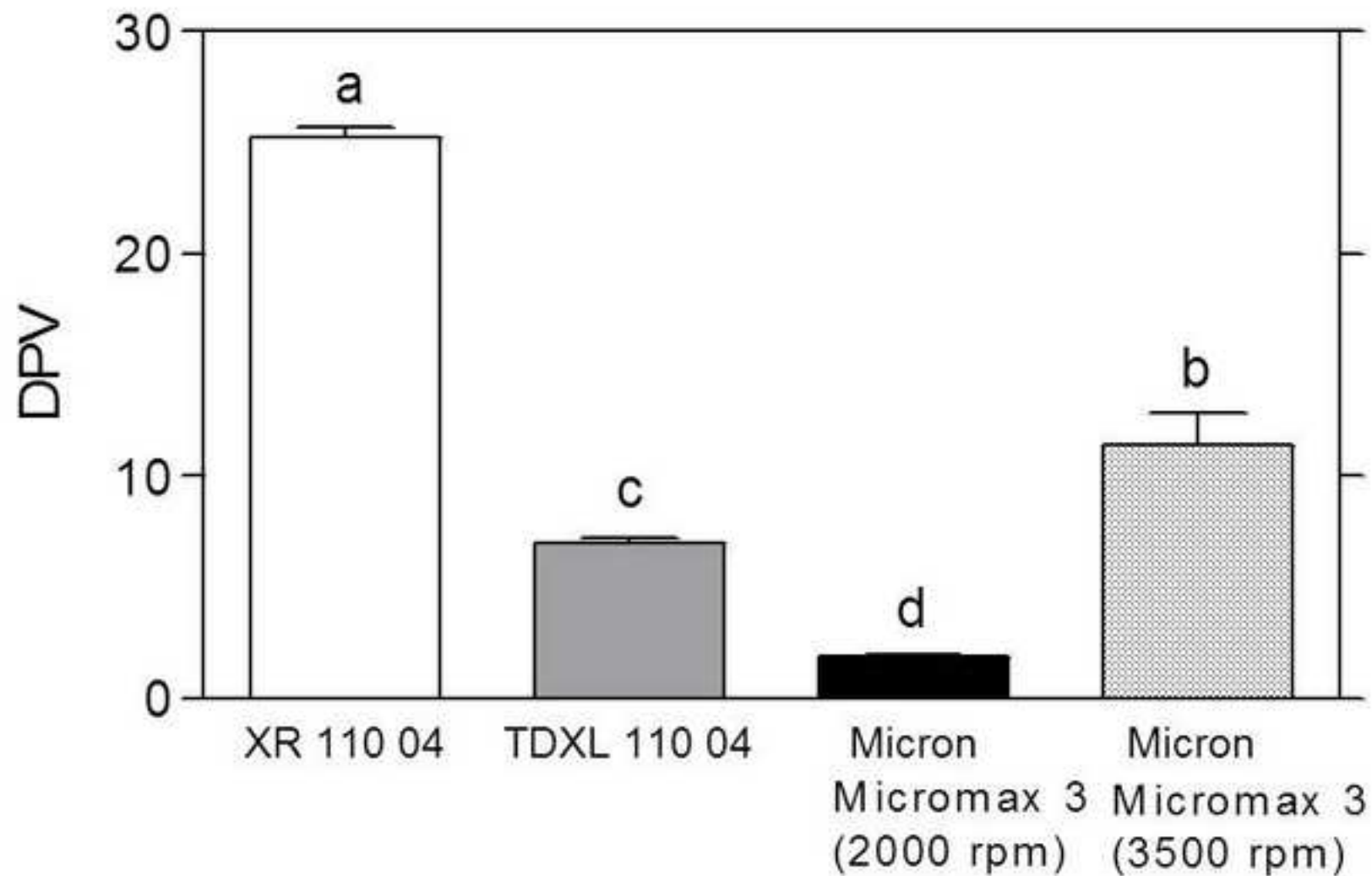
Nozzle type	Boom height (cm)	Average <i>DPV</i>	Drift reduction class (ISO 22369-1)
TeeJet XR 11004	50	25	Reference
	30	12	E
	70	55	No drift reduction
Agrotop TDXL 11004	30	2	C
	50	7	E
	70	11	E
Micron Micromax 3, 2000 rpm	50	2	C
Micron Micromax 3, 3200 rpm	50	11	E

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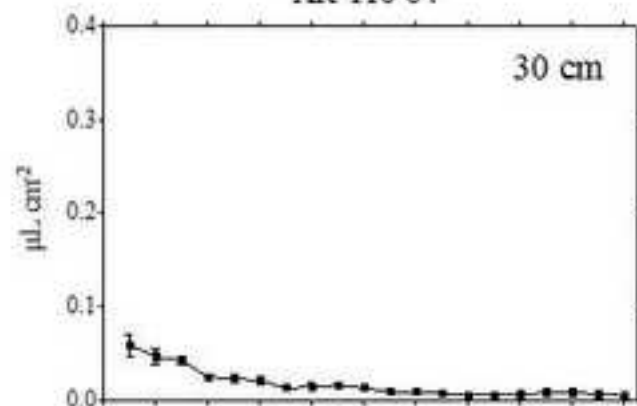




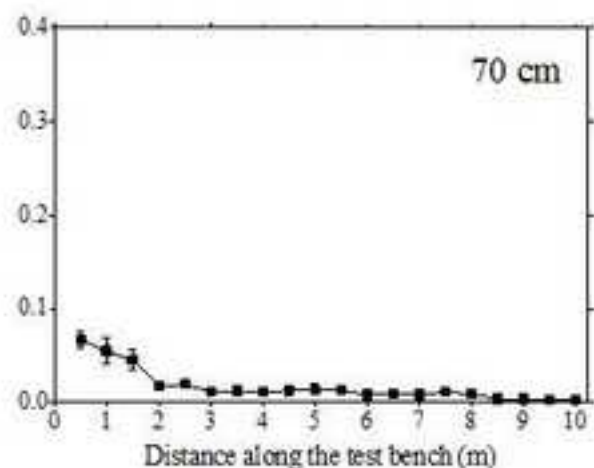
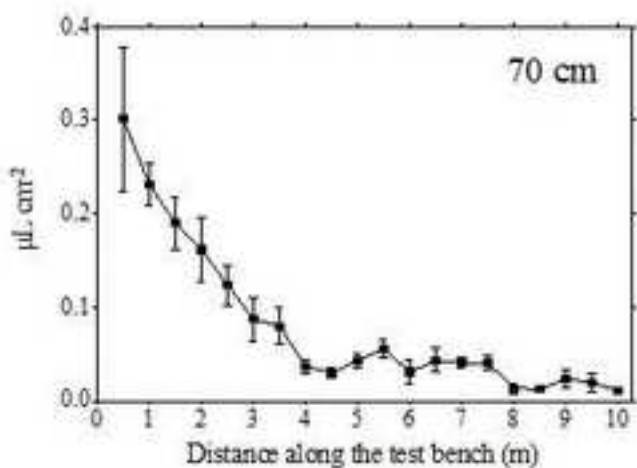
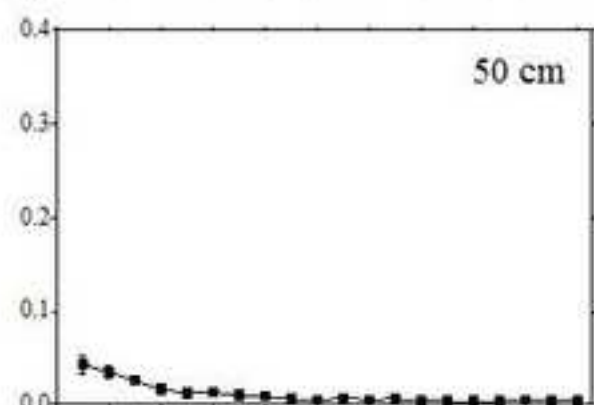
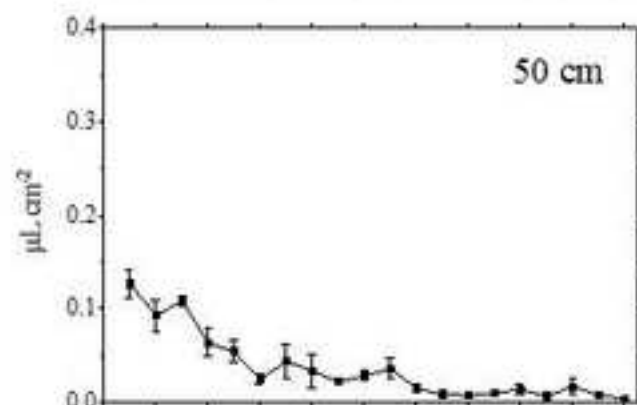
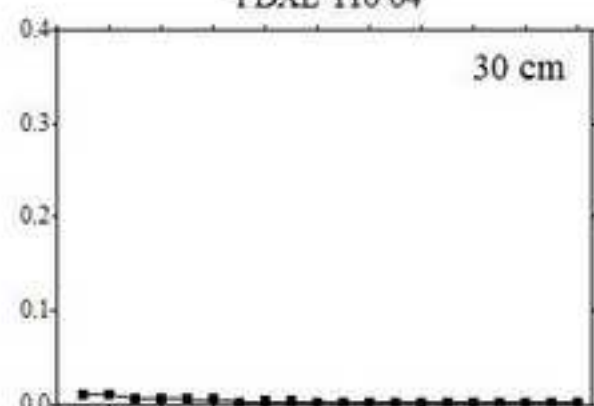


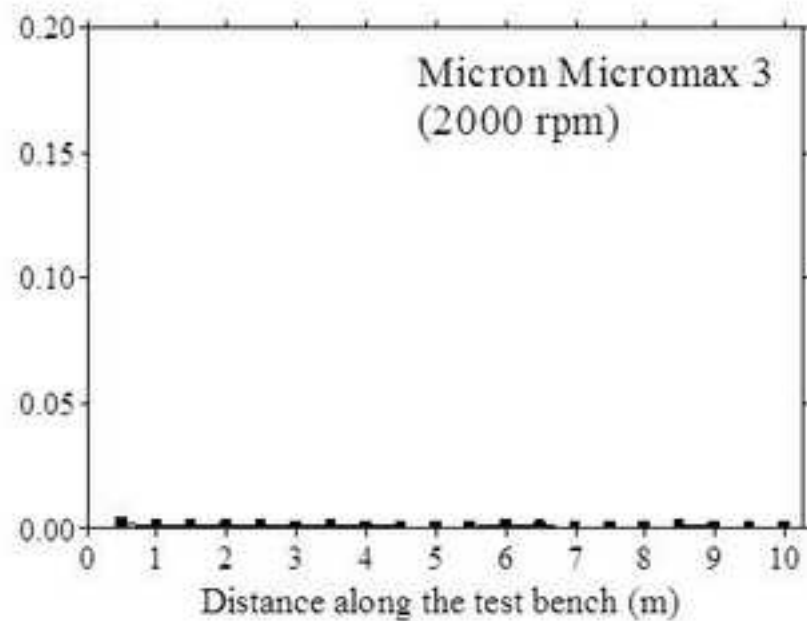
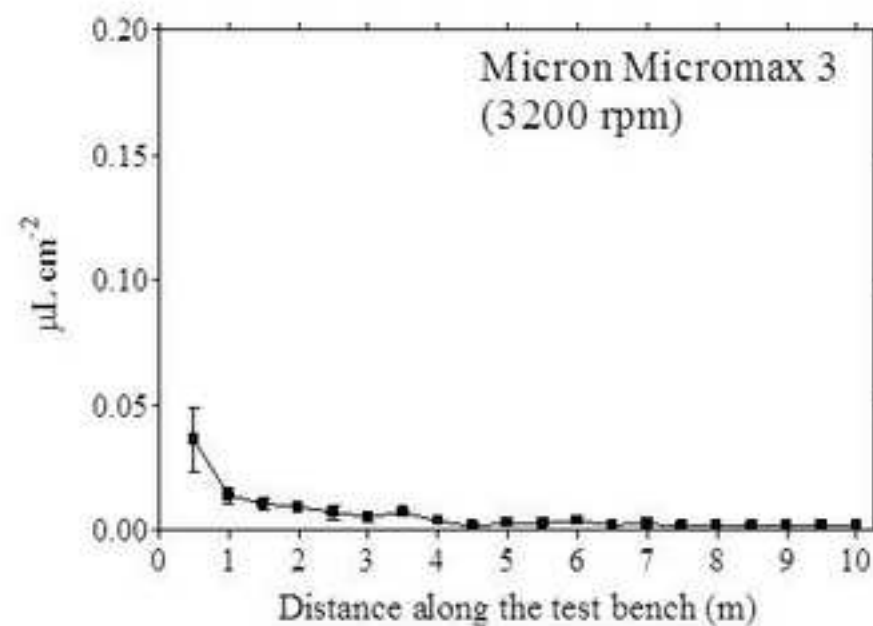
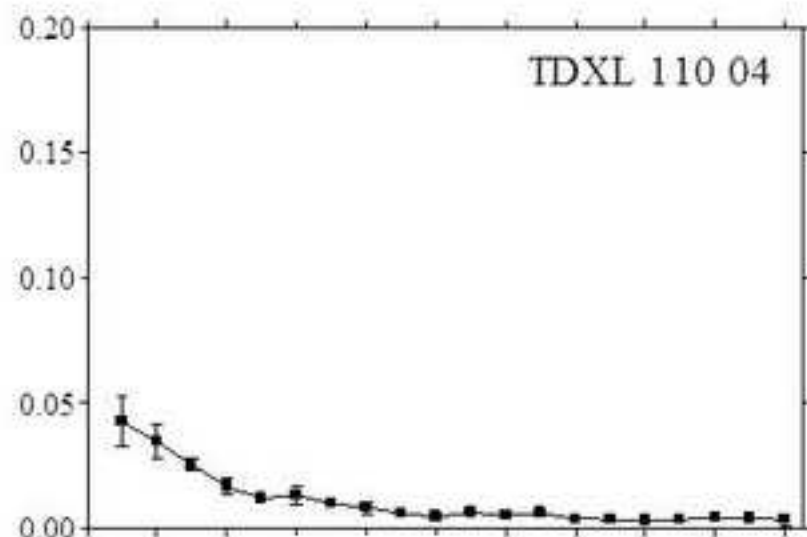
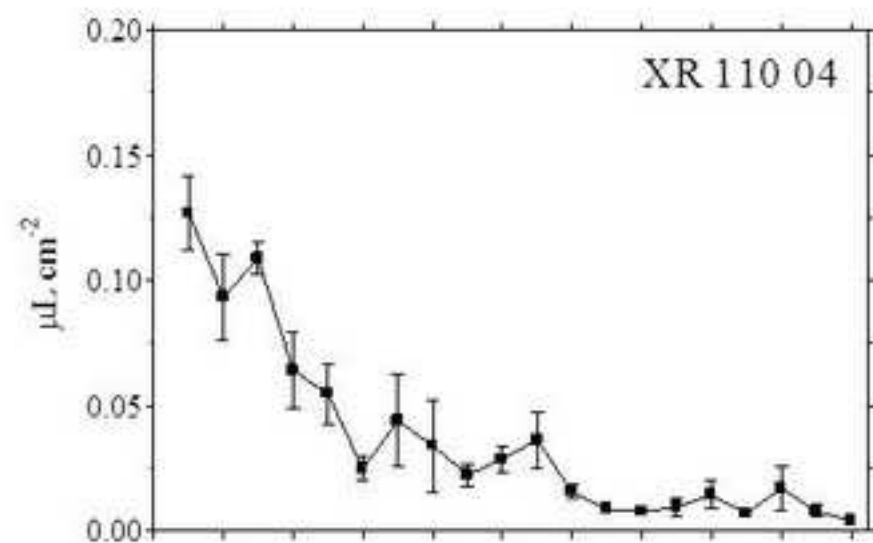


XR 110 04



TDXL 110 04





D_i uncovered collectors ($\mu\text{L cm}^{-2}$)

